Styles of Soft-Sediment Deformation of the Lower Headwall of the Cape Fear Landslide, Offshore North Carolina

Senior Thesis
Submitted in partial fulfillment of the requirements for the
Bachelor of Science Degree
At The Ohio State University

By

Ryan A. Haugh
The Ohio State University
2016

Approved by

Dr. Derek E. Sawyer
School of Earth Sciences

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Abstract

The lower headwall of the submarine Cape Fear Landslide consists of geological features that may indicate ongoing or future episodes of slope failure. In 2014 new 2-D multi-channel seismic data were gathered in this area for the Eastern North American Margin (ENAM) Community Seismic Experiment. Interpretation of these new seismic data may provide important insight into whether or not the Cape Fear Landslide is experiencing ongoing deformation and/or may fail again in the future. Observed features include: potential listric faults, sediment waves, creep deformation and deformation caused by possible fluid flow (e.g., free gas). Other structures such as an unconformity in the lower portion of the lower headwall are also observed. The deformations that appear as faults (or sediment waves) are possibly a cause of lateral stress reductions associated with the release of slope sediments immediately adjacent to the headwall and potentially the added stress of diapirism in the area. Methane gas hydrates are thought to be located near the Cape Fear Landslide. Potential free gas is shown in and near the detachment zone. Potential creep deformation is also identified as being caused by dissociation of methane hydrates and stress related to the upslope region of the Cape Fear Landslide. The tectonic setting and surrounding features of the Cape Fear Landslide are consistent with a retrogressive submarine landslide. Like many other of the large submarine landslides observed on the modern day ocean floors, it is not clear to what extent the Cape Fear slide is currently deforming or if a future failure at this site is possible. Future work is required to answer that question.

Acknowledgements

I would like to thank my supervisor, Dr. Derek Sawyer, whose expertise helped guide me through the interpreting and writing process of my thesis. He also provided me with many helpful articles and research papers that were pertinent to my research. I would like to thank GeoPRISMS who funded the experiment for the data that I used during this thesis, and NSF which funds GeoPRISMS. I would like to thank my parents for always supporting me through the making of my thesis. A very special thanks to all of my professors who have furthered my interests in the Earth sciences (Dr. Panero, Dr. Barton, Dr. Wilson, Dr. Krissek, and Dr. Sawyer). I would also like to thank my friends for giving me support throughout my time at Ohio State.

Introduction and Geologic Setting

The Cape Fear Landslide is one of the largest and best documented of the U.S. Atlantic continental margin mass movement features [*Popenoe et al*, 1993]. It is located approximately 200 km southeast of Cape Fear, North Carolina (Figure 1) and is on the eastern, seaward side of the Carolina Trough, which is Triassic-Jurassic in age [*Hornbach and Lavier*, 2007]. The Carolina Trough formed over 140 million years ago during rifting of the North American and African plates. The Cape Fear Landslide is approximately 30,000 years old (Figure 2). The lower headwall of the Cape Fear Landslide is approximately 2,600 m below the sea surface [*Popenoe et al*, 1993]. It is approximately 25 kilometers long and 120 meters high (Figure 2). This slide occurred in a region of prevalent gas hydrates (as indicated by the regional presence of bottom-simulating reflectors [BSRs]) and active diapirism [*Rodriguez and Paull*, 2000]. The BSR is thought to be the deepest depth at which gas hydrates are stable. There may or may not be free gas located beneath the BSR but it is assumed that hydrates are in the sediments between the seafloor and BSR.

A linear series of salt-cored diapirs aligned with the East Coast Magnetic Anomaly rises from Jurassic rift sediments along the eastern edge of the Carolina Trough intersecting the head of the Cape Fear Slide [*Schmuck and* Paull, 1993]. The salt diapir, located on the seaward side of the lower headwall of the Cape Fear Landslide, is Jurassic in age and was formed during the rift of the North American and African plates (Figure 2). A diapir is defined as a fold in which a mobile core has risen and broken through brittle overlying rock and sediment [*Popenoe et al*, 1993]. The Cape Fear Landslide is an interesting area because of the presence of extruding diapirs and its association with methane gas hydrates in the subsurface [*Popenoe et al*, 1993]. Both of which could be possible mechanisms for triggering landslides at Cape Fear.

In 2014 new 2-D multi-channel seismic data were gathered in this area for the Eastern North American Margin (ENAM) Community Seismic Experiment. The newly acquired seismic data presented many new research opportunities because of the high quality imaging. I aim to analyze some of the structures present in the lower headwall of the Cape Fear Landslide that were not previously seen. These structures include potential listric faults, sediment waves, creep deformation, deformation caused by free gas, deformation caused by diapirism, and indications of an unconformity. The objective of this project is to provide preliminary interpretations on the features located in the lower headwall of the Cape Fear Landslide. These features may or may not be indicative of future slope failure, but the following geological interpretations should provide necessary insight into this question.

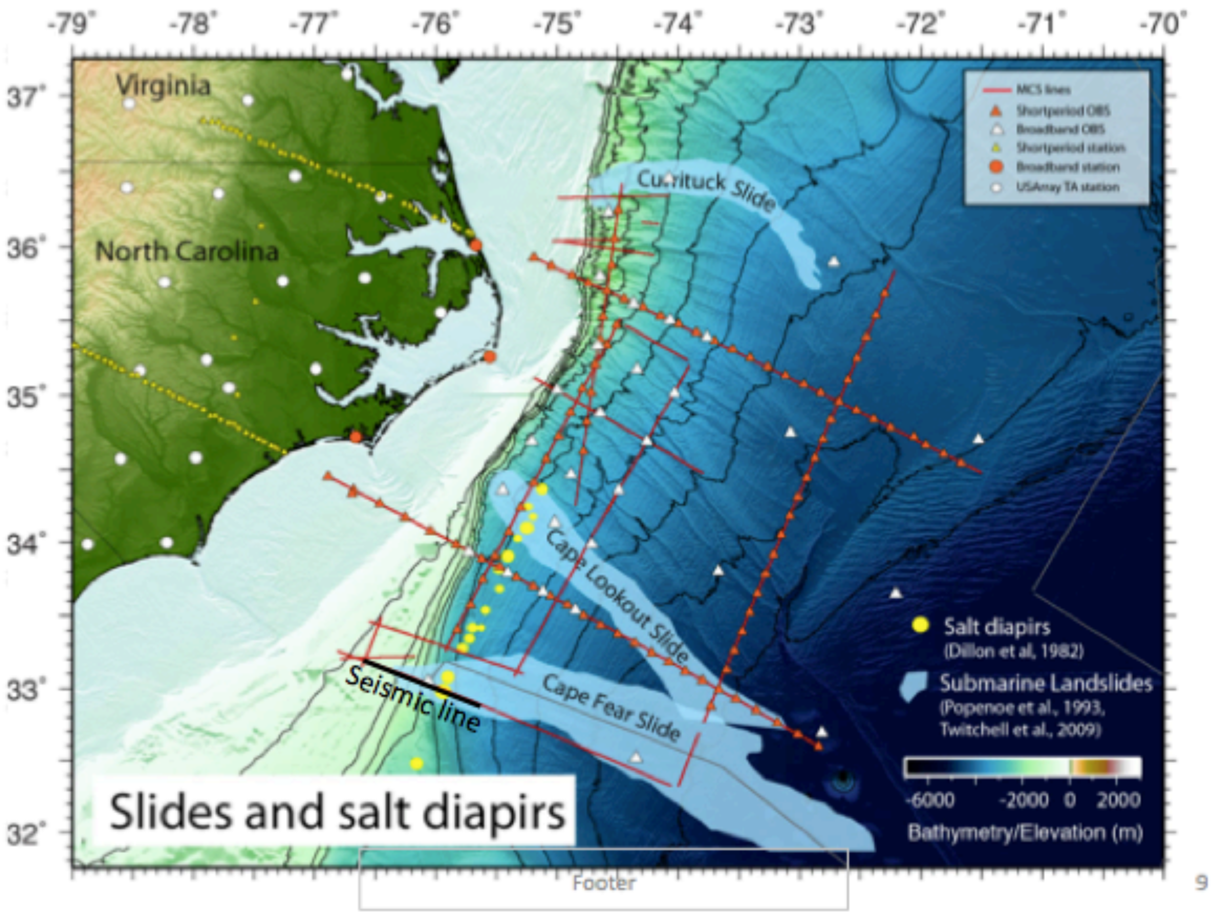


Figure 1: This image represents the salt diapirs and landslides associated with the Carolina Trough. The Cape Fear Landslide is the largest on the U.S. Atlantic margin. The black line on the most southern part of the Cape Fear Landslide identifies the seismic line that is shown in Figure 2. Modified from Cruise Report, 2014.

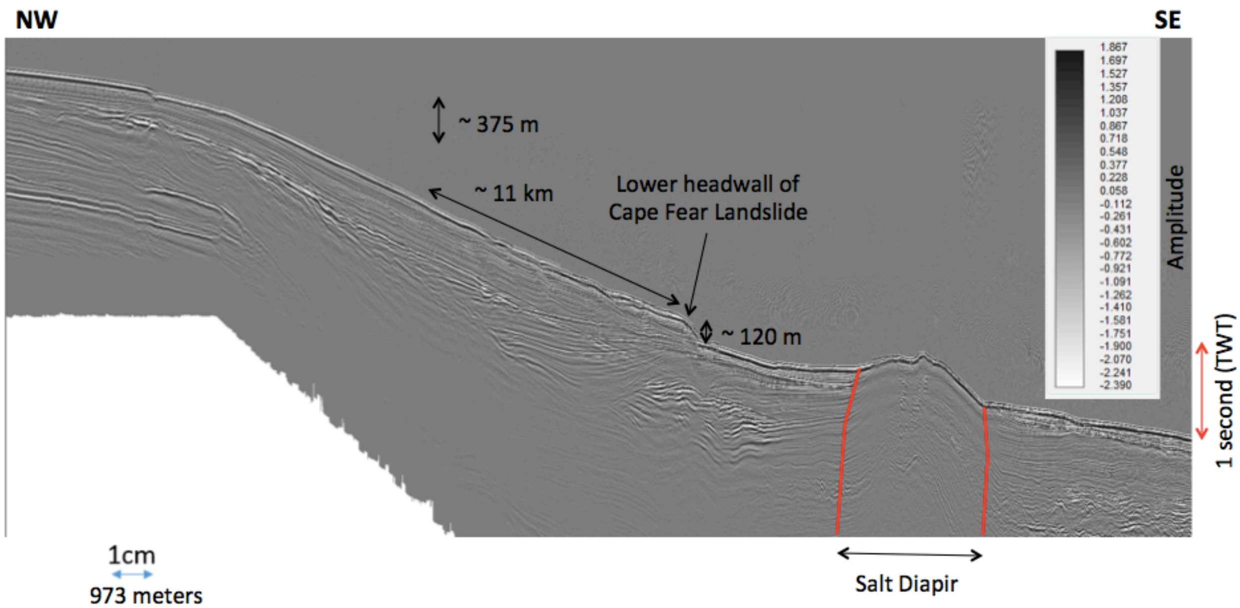


Figure 2: This is the seismic line that was interpreted in this thesis. It is identified in Figure 1 as the black line through the Cape Fear Slide. The lower headwall of the Cape Fear Landslide and salt diapir are observed in this image. The salt diapir is located on the seaward side of the lower headwall. All figures relating to this seismic line are shown in the results section.

METHODS

Seismic Data Acquisition

Data used to make the interpretations and create the figures were acquired for the Eastern North American Margin (ENAM) Community Seismic Experiment. All information in this section was taken from the Cruise Report [*Cruise Report*, 2014]. The objectives of this experiment included collecting an open-access onshore/offshore, active/passive seismic dataset across the Mid Atlantic continental margin that can be used by the community to understand magmatic processes involved in the breakup of Pangaea and opening of the Atlantic Ocean and recent evolution of the margin by dynamic, interrelated processes such as sediment transport, slope failure, salt diapirism and gas hydrate formation and dissociation [*Cruise Report*, 2014].

The cruise acquired 4816 km of seismic reflection data along and across the North Carolina margin. These profiles included two MCS/OBS (MCS – Multi channel Seismic, OBS – Ocean Bottom Seismometer) dip profiles across the entire margin, two ~250-km-long MCS/OBS profiles along the East Coast Magnetic Anomaly, one ~350-km-long MCS/OBS profile along the Blake Spur Magnetic Anomaly, a series of profiles across and adjacent to the Cape Fear slide, a series of profiles across the Currituck Slide area, a series of other profiles intended to capture along-strike variations in sedimentary and crustal structure between the two main profiles, and both strike and dip MCS lines that image salt diapirism and listric faulting along the margin.

The streamer used in the MCS acquisition was 8km long, with 636 hydrophones spaced at 12.5 m apart. The offset distance from the source to the airguns was 186.5 m. Airguns were used as the energy source. There were 5207 shots fired from the airguns with a 25 m shot interval. The four main steps used onboard for the data processing were geometry definition and binning, filtering and data cleaning, velocity analysis and stacking and migration.

Data Interpretation

In order to interpret the deformations seen in the lower headwall of the Cape Fear Landslide, I applied fundamentals of seismic data interpretation to infer geological structures. I focused my analysis on the following structures: faults, diapirism, a detachment zone, migration of free gas, possible creep deformation and an unconformity. Faults can be recognized by a displacement or break in strata (Figure 3). The landslide detachment zone was identified as an irregular reflector cross-cut by the BSR with potential free methane gas in and around it (Figure 4). The salt diapir, as shown in Figure 5, pushes the adjacent strata away. Figure 6 shows continuous sedimentary layers that form a wave-like pattern. An unconformity cuts off multiple layers immediately behind the headwall (Figure 6).

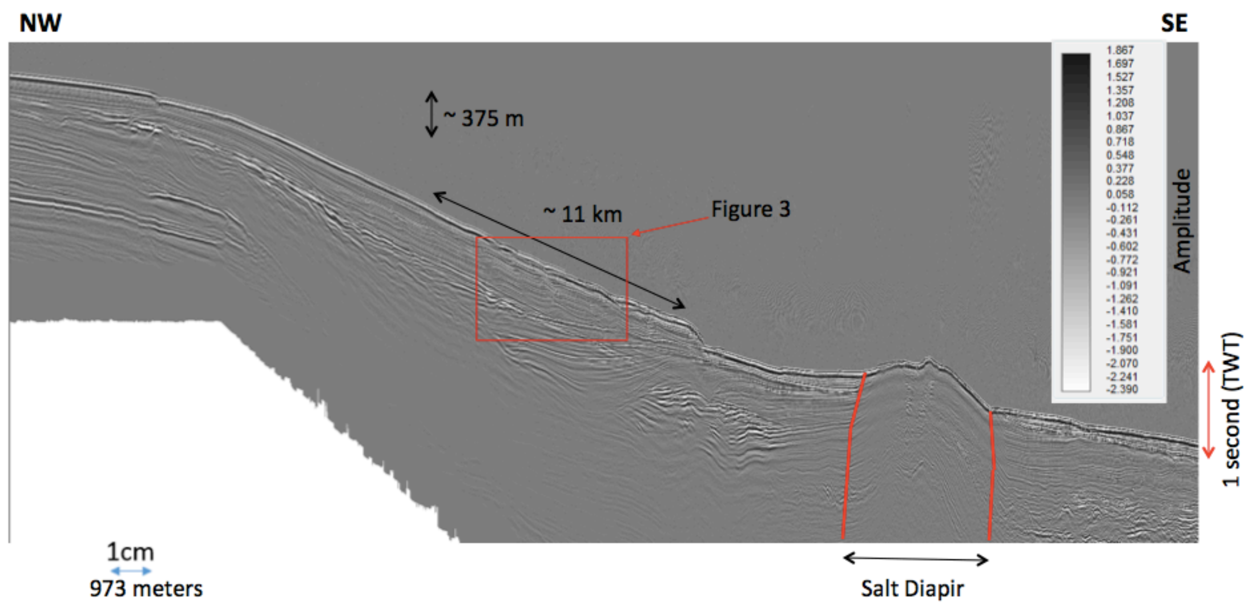
I interpreted the seismic data with Kingdom Suite software. Kingdom Suite allowed me to interpret the entire seismic line and make annotations where necessary. Initial figures were made on the Kingdom Suite software using the annotation tools. After creating the initial figures, they were transferred to PowerPoint. Final figures were created in PowerPoint to add scale bars and other annotations that were not easily made in Kingdom Suite.

RESULTS

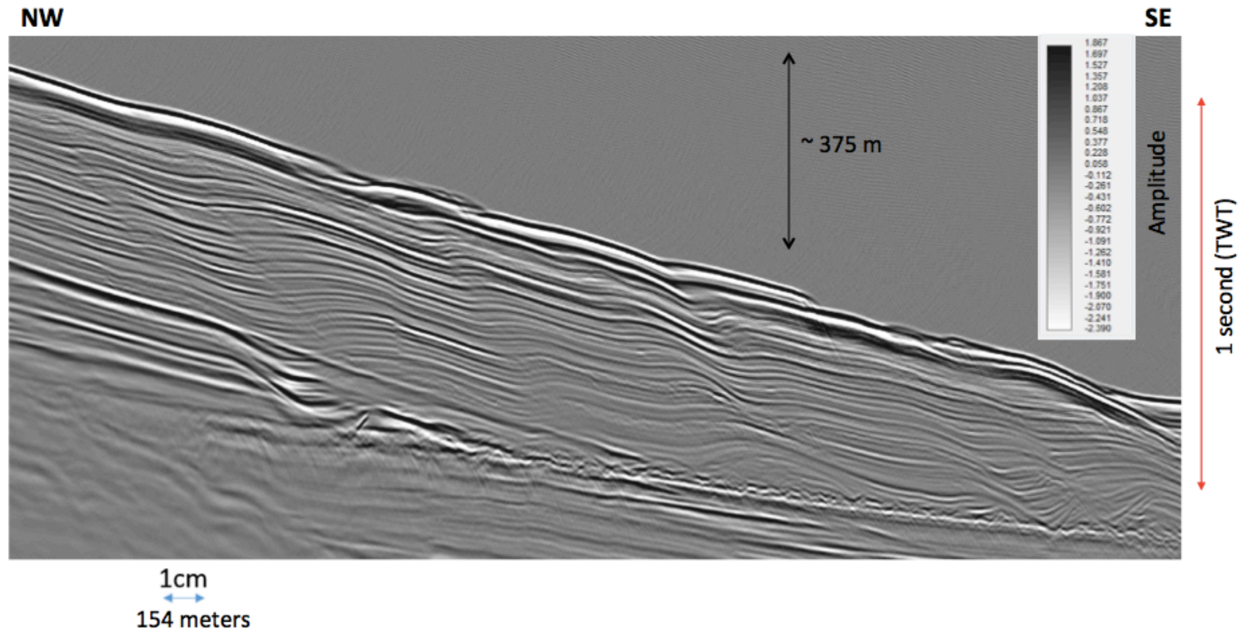
Listric Faults or Sediment Waves

Figure 3 focuses on the area of potential listric faults or sediment waves. There is a broad zone of approximately 11 km that contain these deformations (Figure 3A). The potential faults or sediment waves, represented by a green lines, pass through the uniform layer, represented by the red line (Figure 3c). There are three larger green lines on the left side of Figure 3c that are parallel to each other. The green line to the right is much smaller, but still parallels the larger lines.

(a)



(b)



(c)

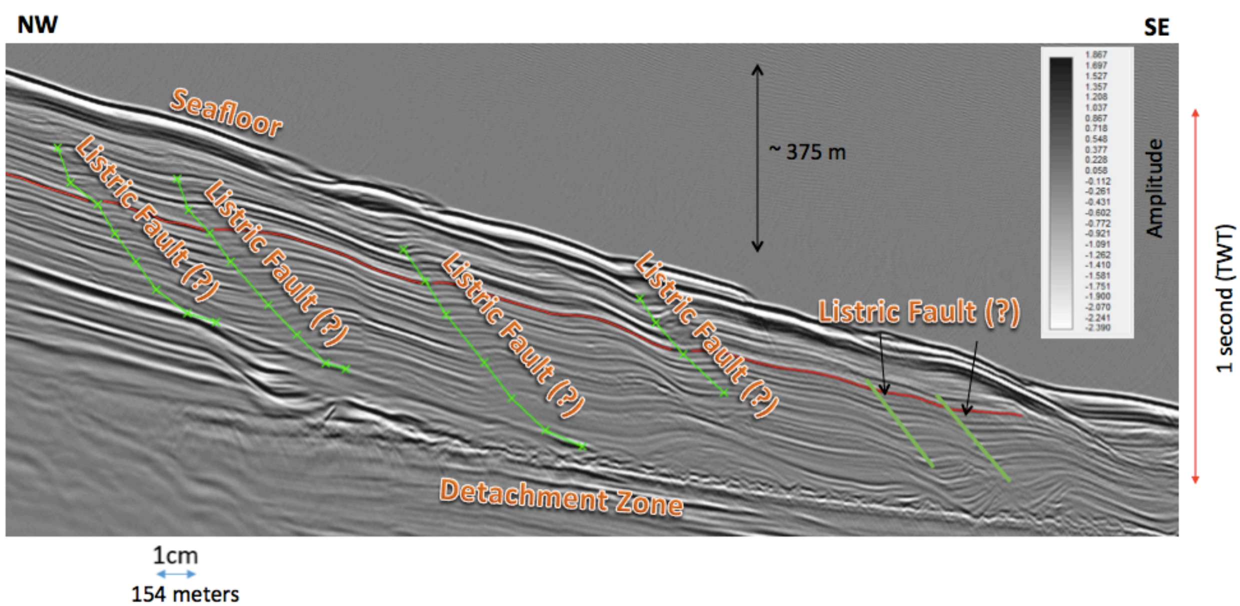
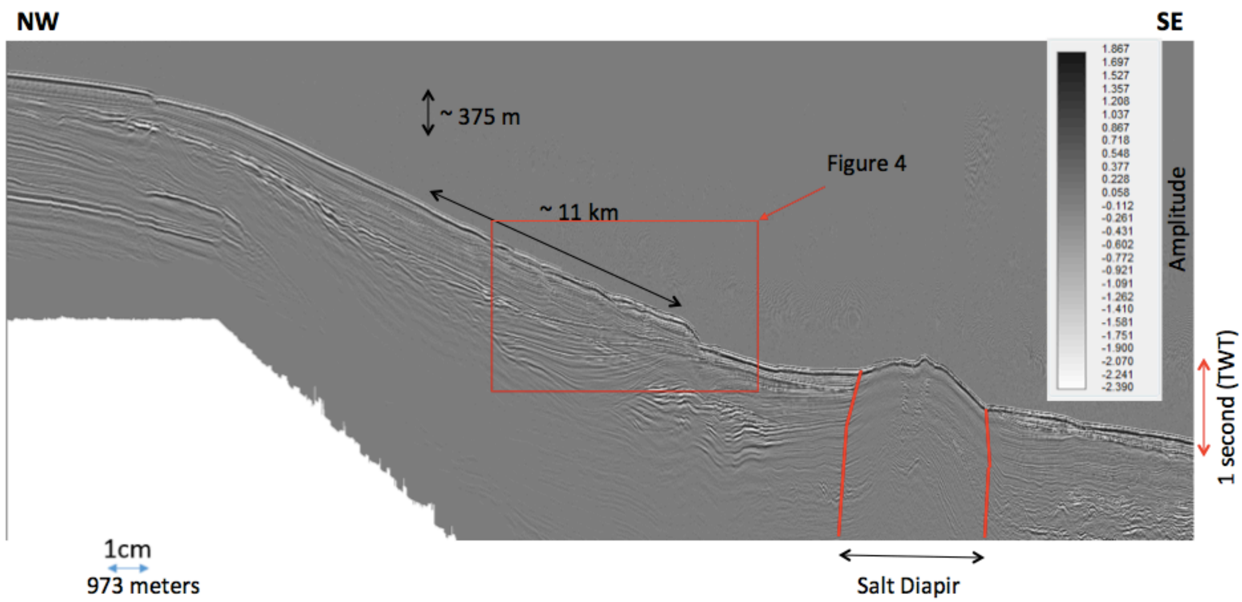


Figure 3: Potential listric faults or sediment waves in the lower headwall of the Cape Fear Landslide. Figure 3a shows area of interpretation for Figure one as it relates to the whole seismic data set. Figure 3b shows seismic data before interpretation. The red line in Figure 3c shows a uniform layer through the landslide. The green lines shows the potential faults or sediment waves.

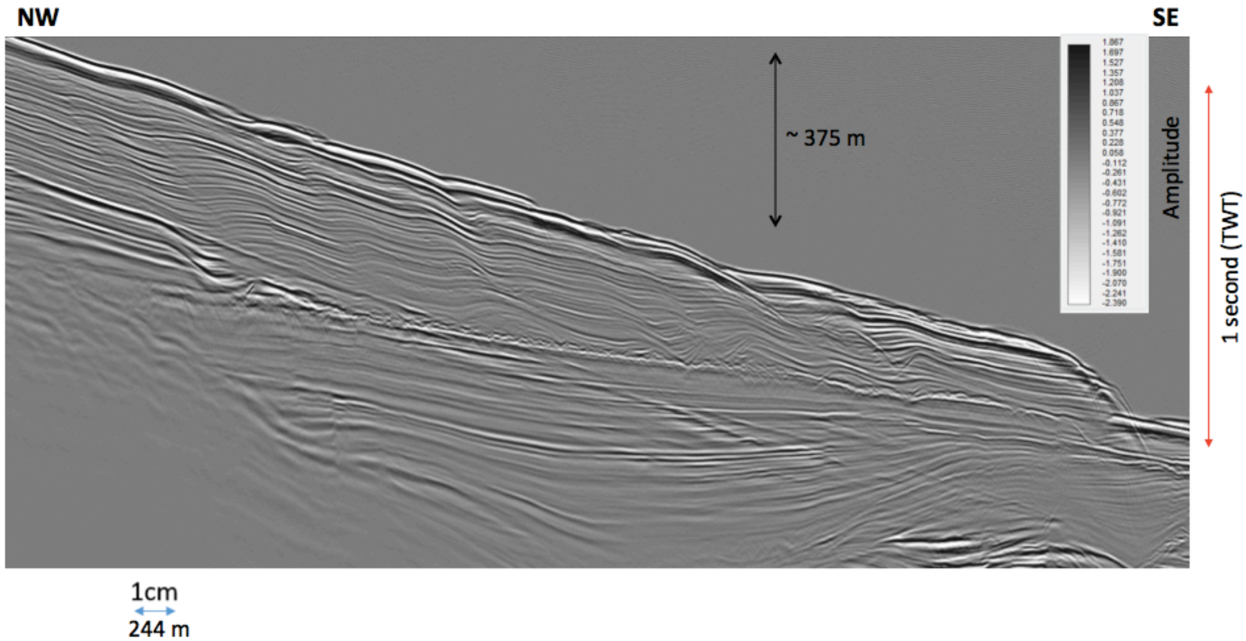
Detachment Zone

Figure 4 identifies the location of the detachment zone. The red line shown in Figure 4c shows the detachment along which the Cape Fear Landslide failed. The detachment zone lies above the BSR.

(a)



(b)



(c)

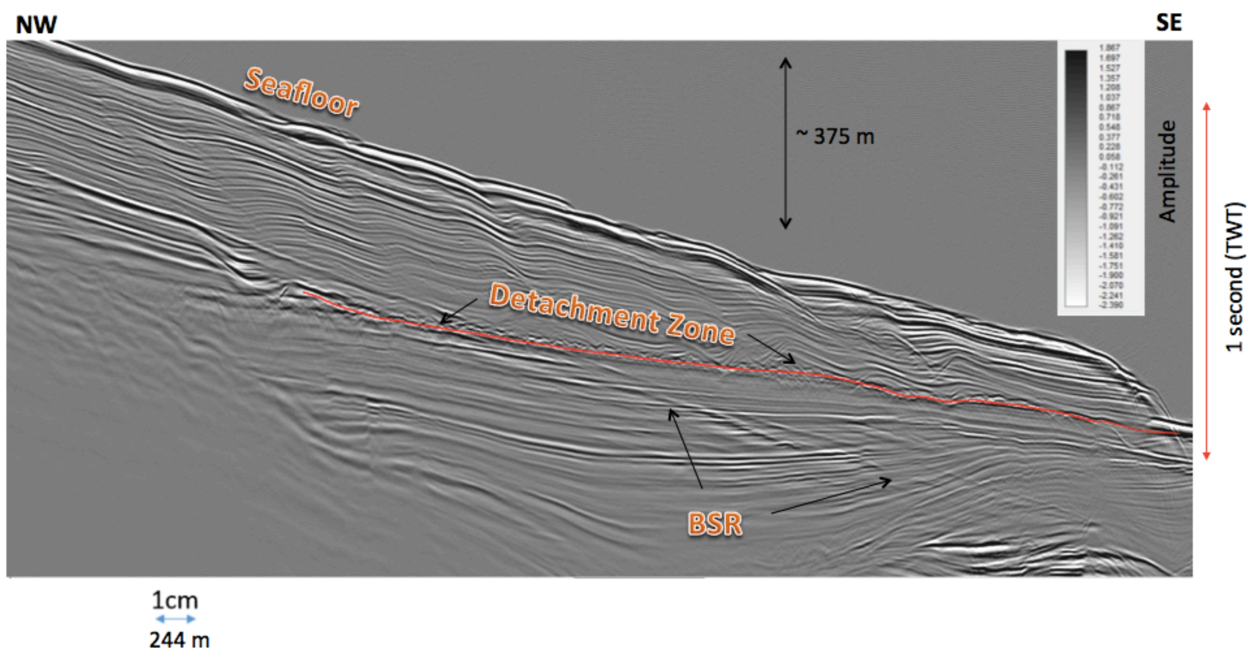


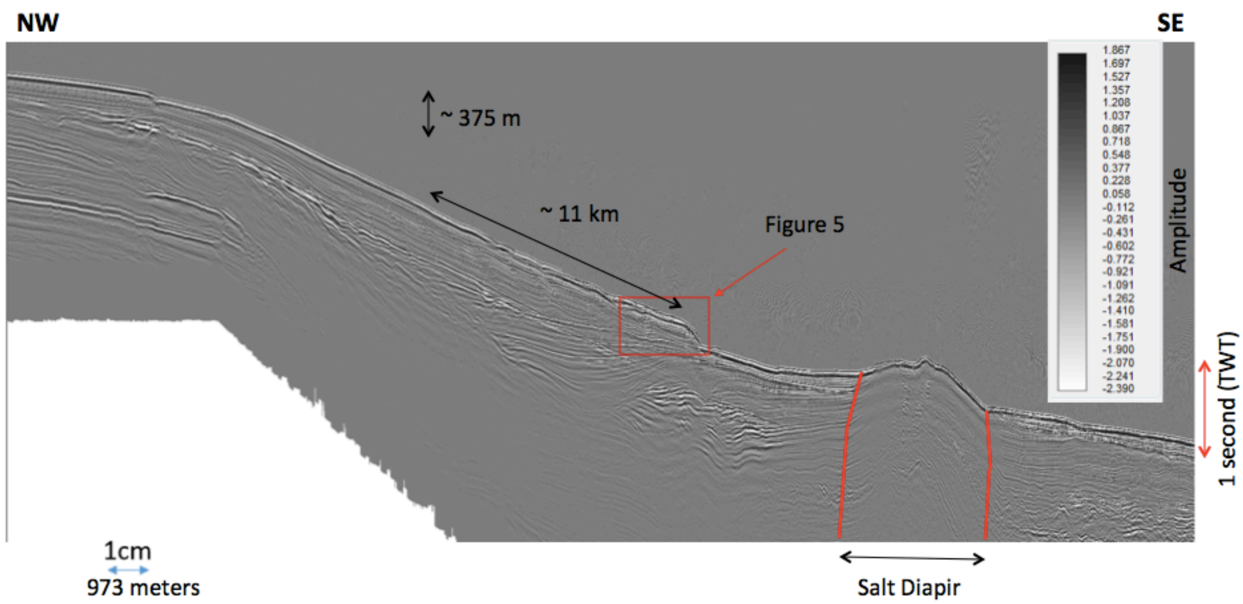
Figure 4: This shows the detachment zone and potential migration of free gas within and around the detachment zone. Figure 4b is uninterrupted seismic data. The red line in Figure 4c shows the boundary of the detachment zone. The detachment zone refers to the area where the sediment and rock layers involved in the landslide are separated from the sediment and rock layers that remain stable. There are examples all along the detachment zone, but this is the most heavily concentrated area. The area shows irregular deformation of continuous strata.

Unconformity and Potential Creep Deformation

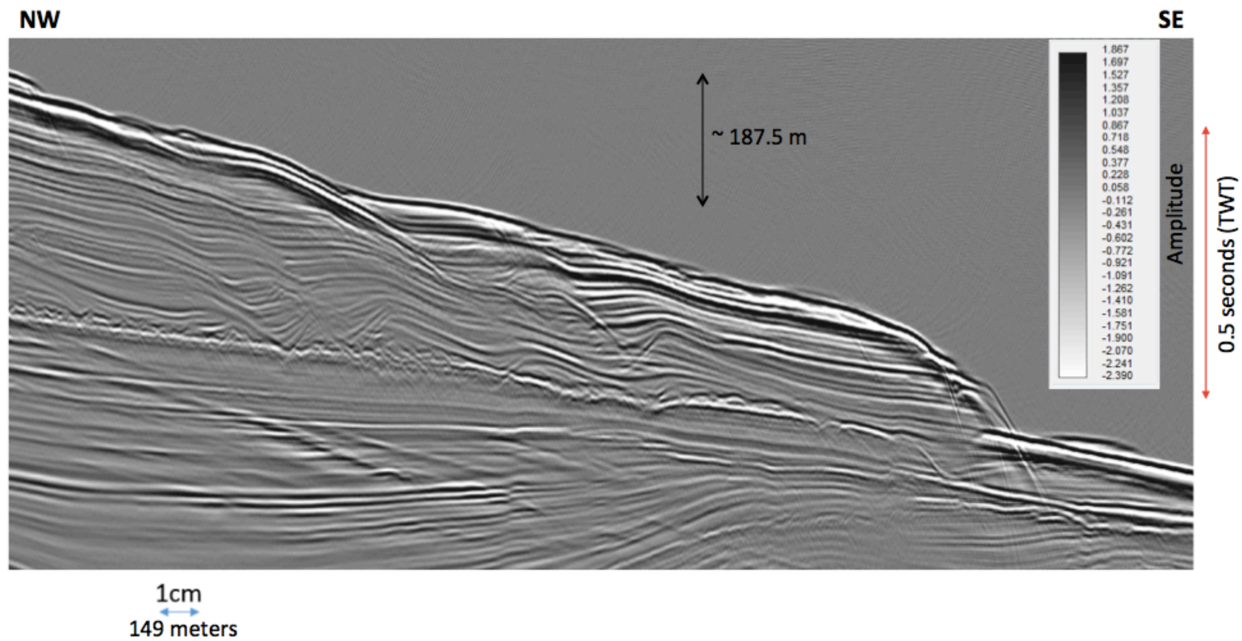
At the top of the red line in Figure 5c, it is clearly shown that the reflector coming in from the left side of the line is cutting through the reflector on the right side of the line. As you move down the line, it becomes more difficult to trace unconformities.

The red lines in Figure 5d identifies an example of the areas of possible creep deformation in the lower headwall of the Cape Fear Landslide. The strata that is cut by the green lines seems to be continuous, but have similar characteristics that you look for when identifying a fault or sediment wave. For example, the wavy characteristics of the strata look similar to displacement caused by a fault or deformation seen in sediment waves.

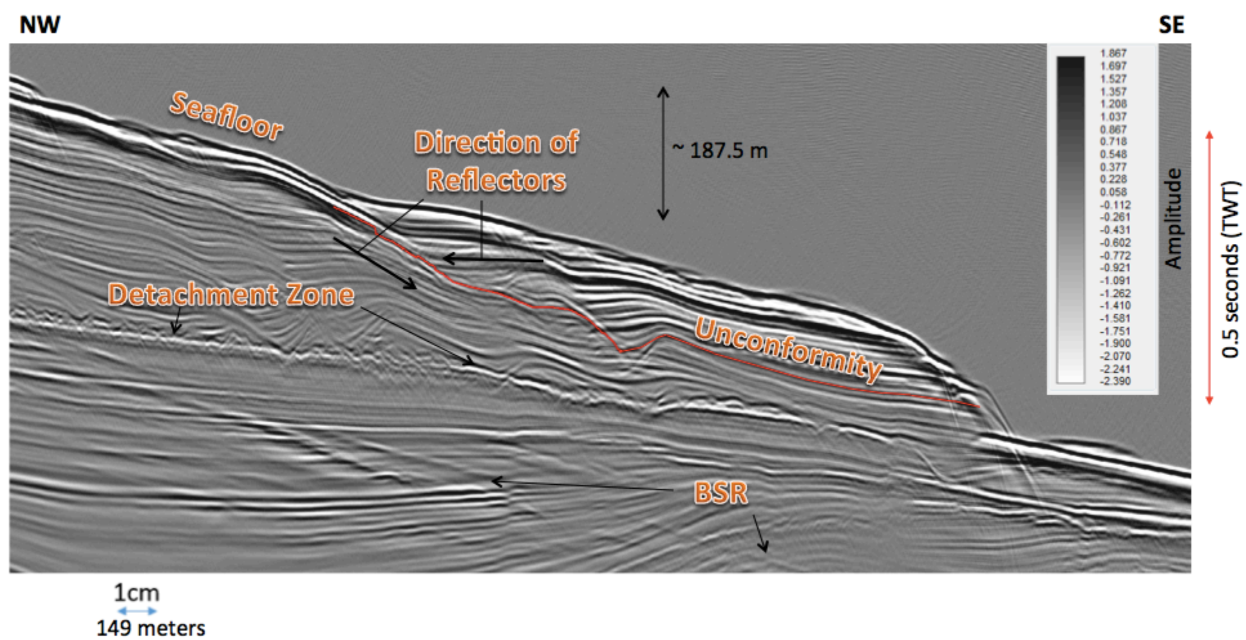
(a)



(b)


NW
SE
~ 187.5 m
1.867
1.697
1.527
1.357
1.208
1.037
0.867
0.718
0.548
0.377
0.228
0.058
-0.112
-0.261
-0.431
-0.602
-0.772
-0.921
-1.091
-1.262
-1.410
-1.581
-1.751
-1.900
-2.070
-2.241
-2.390
Amplitude
0.5 seconds (TWT)
1cm
149 meters

(c)


NW
SE
Seafloor
Direction of Reflectors
~ 187.5 m
Detachment Zone
Unconformity
BSR
1.867
1.697
1.527
1.357
1.208
1.037
0.867
0.718
0.548
0.377
0.228
0.058
-0.112
-0.261
-0.431
-0.602
-0.772
-0.921
-1.091
-1.262
-1.410
-1.581
-1.751
-1.900
-2.070
-2.241
-2.390
Amplitude
0.5 seconds (TWT)
1cm
149 meters

(d)

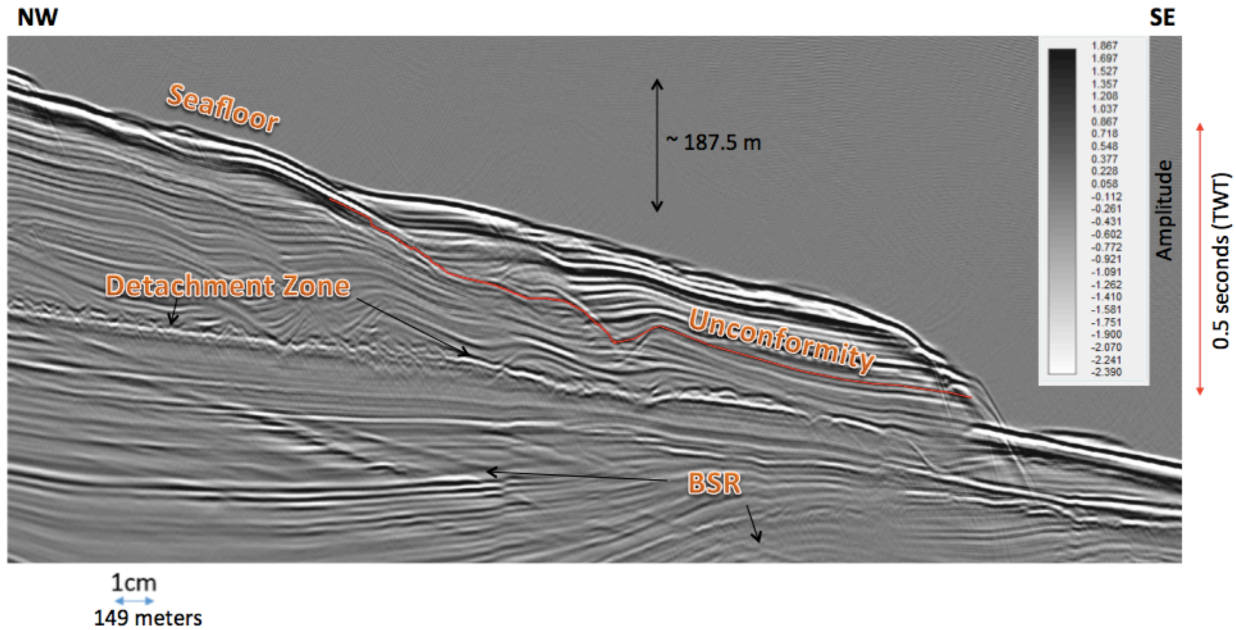
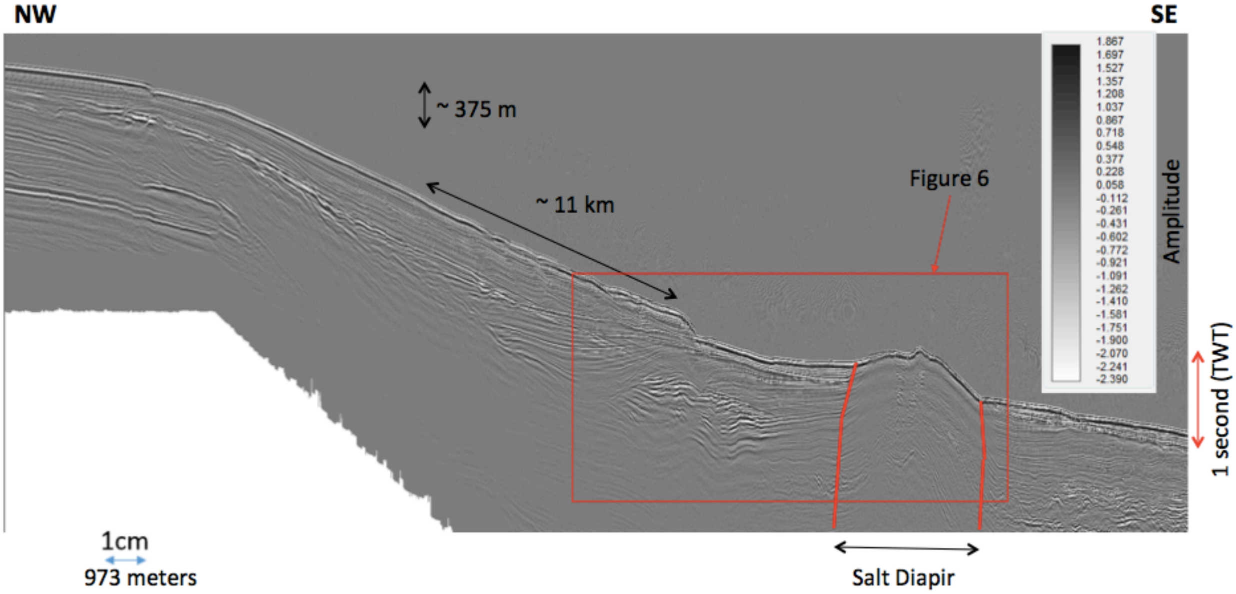


Figure 5: Unconformity seen in the lower headwall of the Cape Fear Landslide and potential creep deformation. Figure 5b shows the uninterpreted seismic data. The red line in Figure 5c indicates the boundary at which an unconformity is identified. The red lines in Figure 5d show an example of the areas of possible creep deformation in the seismic data set. The beds appear to be continuous, but are they are also wavy. Potential faults could form here in the future, but these data alone do not provide evidence for faulting.

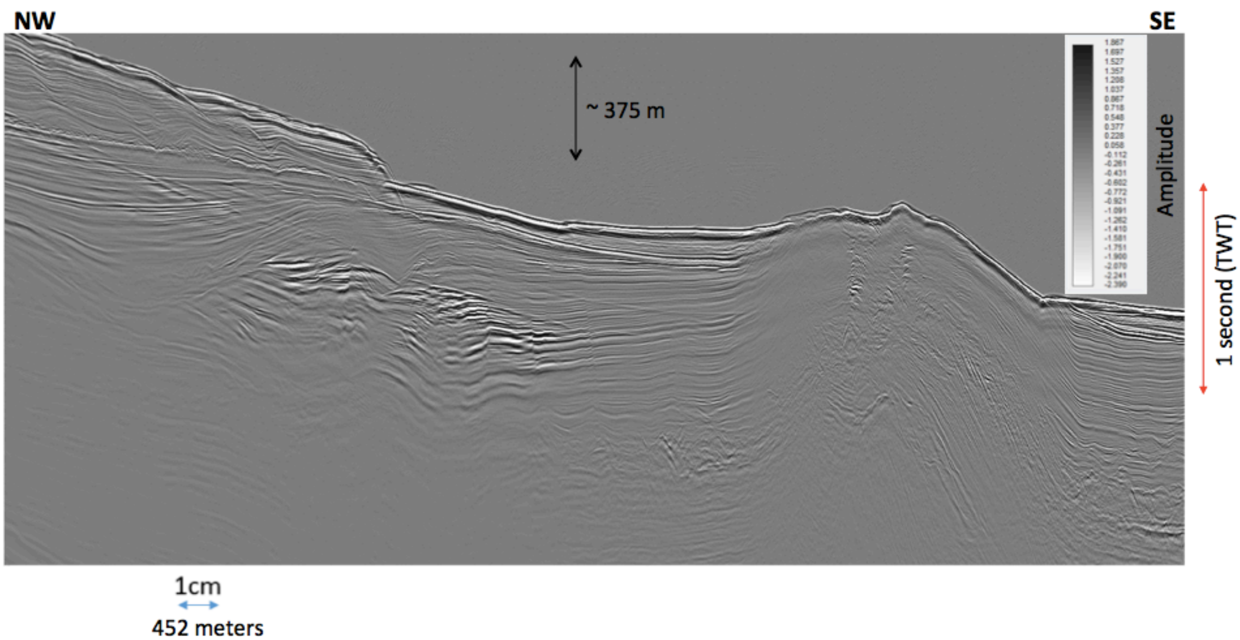
Salt Diapir

The red circle in Figure 6c shows the area of rising salt. The wavy lines in the circle and the strata that are curving upward near the diapir mound show that there is an upward migration of the salt. The lower headwall (Figure 4 and 5) is also shown in relation to the salt dome.

(a)


NW
SE
~ 375 m
~ 11 km
Figure 6
Amplitude
1 second (TWT)
1cm
973 meters
Salt Diapir

(b)


NW
SE
~ 375 m
Amplitude
1 second (TWT)
1cm
452 meters

(c)

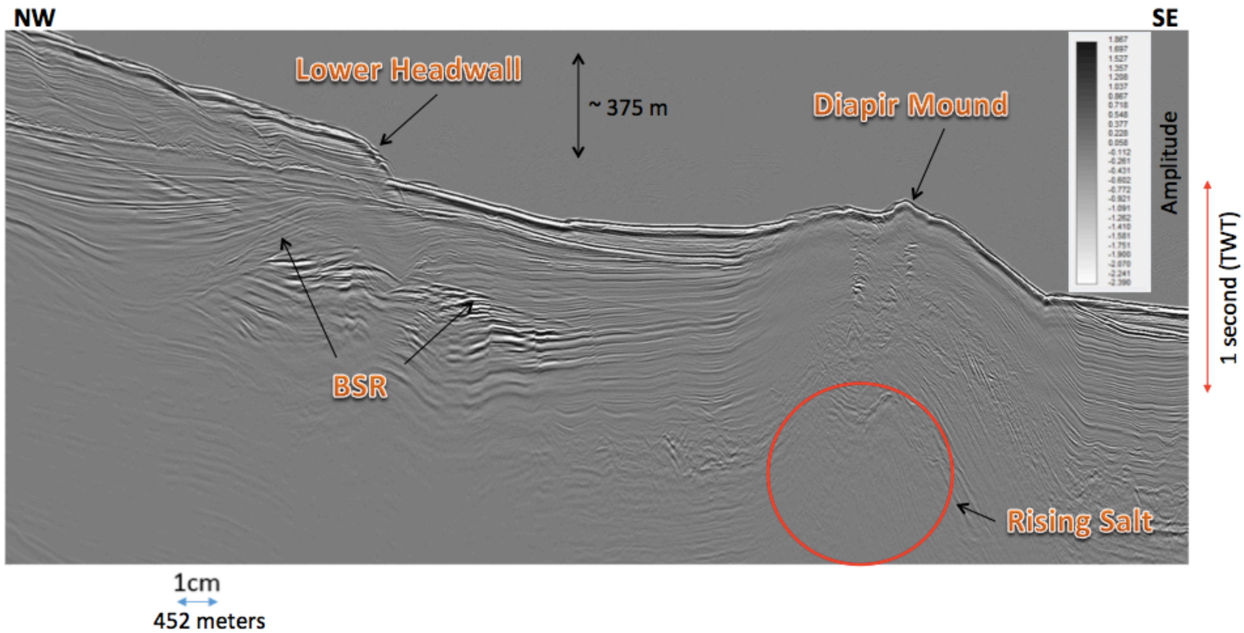


Figure 6: Salt diapir on the seaward side of the lower headwall of the Cape Fear Landslide. Figure 6b shows the uninterpreted seismic data. The red circle in Figure 6c identifies the rising salt. The upward curve of the rock layers near the diapir mound show the direction of the rising salt.

DISCUSSION

Formation of Potential Listric Faults or Sediment waves

The lower headwall of the Cape Fear Landslide shows a possibility of listric faults or sediment waves (Figure 3). These were most likely a result of extension and retrogressive failure. Since the Cape Fear Landslide is in an area of extension, the green lines shown in Figure 3 are most likely listric faults. Listric faults are defined as faults with a concave upward surface, with a dip that increases with depth [*Basic Structural Features II*]. According to the seismic data, there is no break observed in the strata as shown in Figure 3. This could mean that these features are sedimentary in origin, perhaps sediment waves, but the uniform pattern and tectonic setting of the deformations suggests that these are potentially developing listric faults. Closer to the lower headwall these listric faults disappear and they all seem to stop forming once the unconformity is reached. The significance of this unconformity is unclear at this time.

Sediment waves are defined as being created beneath currents flowing across a seabed, in the form of either downslope-flowing turbidity currents or alongslope-flowing bottom currents [*Wynn and Stow*, 2002]. They are observed on the continental shelf in muddy prodeltas, and are often marked by the presence of gas in the upslope location [*Katsman*, 2013]. The features observed in Figure 3 may be sediment waves that formed previously to the creation of the Cape Fear Landslide. Figure 7 shows an example of sediment waves located in the Blake Ridge region, which is also a part of the Carolina Trough, but to the south of the Cape Fear area. The characteristics of these deformations that lead me to believe they are not sediment waves: (1) parallelism between the crests of the undulations and bathymetric contours over a wide range of orientations and (2) steep flanks of the undulations (up to ~40) [*Shillington et al*, 2012]. The sediment waves observed in Figure 7 are much more irregular and do not show parallelism such as the deformations seen in Figure 3. These characteristics lead me to believe that the deformations located in the lower headwall of the Cape Fear Landslide (Figure 3) are listric faults.

According to Hornbach and Lavier (2007), at least 5 major landslides have likely occurred there within the past 30,000 years. If the features identified in Figure 3 are developing listric faults, then there could be another landslide episode as faults continue to develop. Over time, the weight of the sediment and other contributing stress factors could possibly trigger another landslide.

Deformations Caused by Potential Free Gas

There is possibly an accumulation of free gas in and around the detachment zone (Figure 4). The stability of gas hydrates in the sediment column may be strongly influenced by changes in sea level [*Hornbach and Lavier*, 2007]. Popenoe et al. (1993) and Schmuck and Paull (1993) inferred that there was a significant presence of methane hydrates and free gas below the lower Cape Fear Landslide, which lead to another hypothesis that sea level lowering or bottom water temperature changes may have dissociated hydrates, released gas, and reduced sediment cohesion in the region [*Hornbach and Lavier*, 2007]. As the gas hydrates start to dissociate, free gas and water will enter the pore space of the landslide sediment and cause deformation of the affected strata.

According to Katsman (2013), creep deformations may occur in the downslope region as a result of gas that is located in the upslope region. As gas starts to release in the upslope region, small fractures will form and the sediment will start to act more plastically [*Katsman*, 2013]. This weakening of the sediments in the upslope area will start to create creep deformations in the downslope area, ultimately weakening the landslide as a whole. Figure 8 shows an example of how creep deformation may occur. This idea could potentially relate to the structures identified in Figure 5.

Figure 5 also introduces a few more questions. This area was one of the hardest to interpret. The continuous strata indicate that there are no faults or fractures along the red lines (Figure 5d), but the wavy pattern of the rock layers indicates that deformation has occurred there. This could be due to a combination of deformation caused by the release of free gas near the detachment zone and creep deformation originating in the upslope region. These occurrences could have caused microfractures in the sediments that are smaller than the seismic data could resolve. Over time these microfractures may form a larger fault, which could lead to the formation of another listric fault.

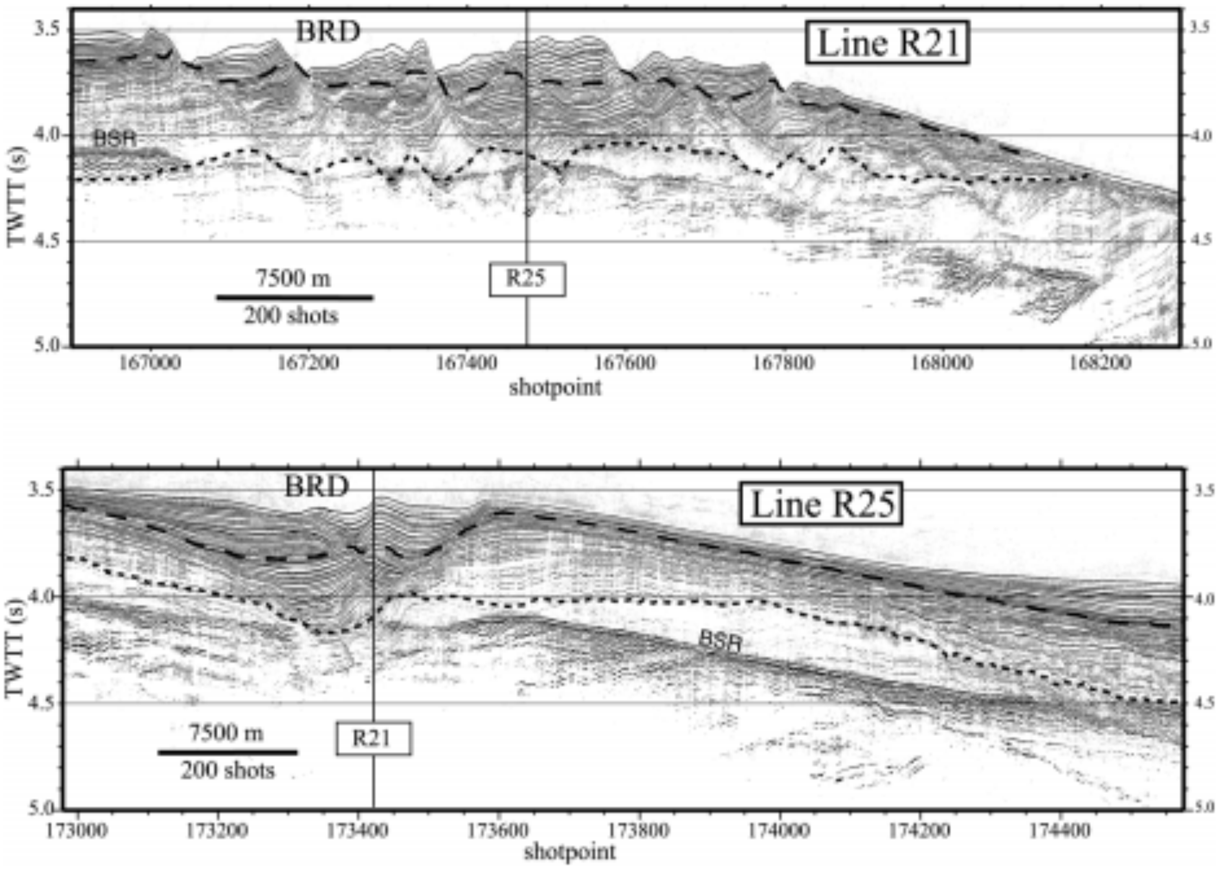


Figure 7: Line R25 shows rapidly deposited post 2.5 Ma sediments that have filled the Blake Ridge depression. Line R21 shows numerous small sediment waves on the northeastern side, which grow into large sediment waves within the Blake Ridge Depression [*Holbrook et al.*, 2002]. The sediment waves in Line R21 are used as a reference to what sediment waves look like in seismic data.

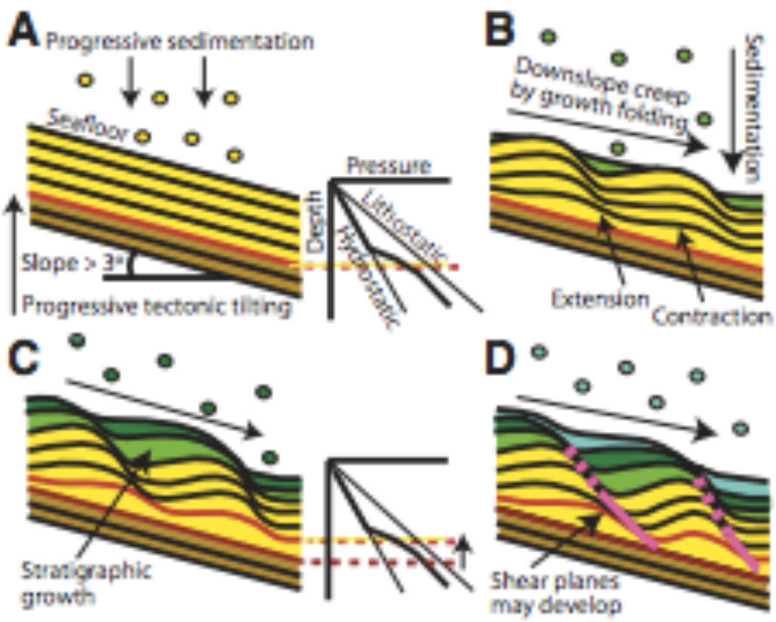


Figure 8: Conceptual model for creep folds. 8A shows rapid sedimentation combined with tectonic tilting that leads to elevated pore pressure and weak regions within the sediment. 8B shows downslope creep occurring by folding above weak regions. 8C shows ongoing sedimentation, tectonic tilting and deformation, which cause evolution of pore pressure regime and strength profile of sediments. 8D shows shear planes that could develop along the bedding planes between folds [*Shillington et al.*, 2012].

CONCLUSIONS

My goal was to interpret a series of conspicuous features in the area immediately upslope of the lower headwall of the Cape Fear Landslide. These features may or may not be indicative of future slope failure. The newly acquired seismic data provided by the Eastern North American Margin (ENAM) Community Seismic Experiment open doors to many new interpretations and research possibilities. The potential listric faults that have been identified in Figure 3 are consistent with the passive margin setting resulting from rifting the North American Plate and African plate during the Jurassic period. The presence of smaller, but similar, faults in the area could possibly be developing extensional faults. The tectonic setting and surrounding features of the Cape Fear Landslide indicate that this is a retrogressive submarine landslide. The deformation potentially caused by free gas of methane hydrates (Figure 4) is interesting in that the deformation may have originated in the upslope area, which could have potentially caused deformation creep in the lower head wall (Figure 5), as predicted by Katsman (2013). Sediment deformations that have been identified in Figure 5 may have been caused or affected by free gas in the upslope area. This free gas could have affected the strength of the sediments associated with the landslide along with the diapirism on the seaward side of the Cape Fear Landslide. Although the rate at which the diapir rises may not be enough to trigger a landslide, the addition of possible gas from dissociated methane hydrates could potentially cause a future landslide.

Recommendations for Future Work

The data presented herein and the other data collected by the Eastern North American Margin (ENAM) Community Seismic Experiment (*Cruise Report*, 2014) provide many opportunities for future research. New fields of study that could use this information include any passive margin landslides or areas of submarine environments affected by the dissociation of methane hydrates. Submarine landslides that are near salt diapirs could also refer to this data. Future research ideas that could be pursued in the Cape Fear Landslide area include a more detailed examination of the combination of the affect of rising salt in the area and dissociation of methane hydrates. A Mohr's circle diagram could be made involving a combination of both stresses on the area. Other research could involve gathering sediment core from the lower head wall of the Cape fear Landslide. This would allow researchers to date the sediments. This could also confirm the interpreted structures and give clues to deformations that are caused by extension and free gas. New core data could also give more evidence to the unconformity shown in the lower headwall of the Cape Fear Landslide.

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